

1 OPTICAL WAVEGUIDE WITH MULTIPLE CORE LAYERS AND METHOD
2 OF FABRICATION THEREOF
3
4

5 FIELD OF THE INVENTION
6

7 This invention relates to an optical waveguide with
8 multiple core layers and a method of fabrication
9 thereof.
10

11 In particular, the invention relates to a doped planar
12 waveguide with multiple core layers and which includes
13 both active and passive components and to a method of
14 fabricating a planar waveguide for an optical circuit
15 in which the core is composed of layers of different
16 materials.
17

18
19 BACKGROUND OF THE INVENTION
20

21 Planar waveguides can be passive devices or can
22 include active components; for example, modulators,
23 couplers, and switches. Planar waveguides
24 incorporating active components are extremely
25 advantageous as they can be used to provide integrated
26
27

1 optic packages which can serve as complete transmitting
2 modules with, for example, components for amplitude or
3 phase modulation, or multiplexing in an optical
4 communication network.

5
6 Rare earth doped fibre amplifiers, for example erbium
7 or neodymium doped fibre amplifiers, are known to have
8 several advantages in optical communication networks
9 such as high gain, low noise, high power conversion
10 efficiency and wide spectral bandwidth. The present
11 invention seeks to provide the same advantages in
12 planar rare earth doped waveguides and moreover to
13 provide a laser waveguide amplifier which can be used,
14 for example, in an optical communication network to
15 amplify attenuated signals.

16
17 Planar waveguide technology is important in the
18 fabrication of lasers and optical amplifiers due to the
19 superior stability, compact geometry of planar
20 waveguide technology. Also, active components, for
21 example modulators, can be integrated into the planar
22 device.

23
24 A variety of techniques, including flame hydrolysis
25 deposition (FHD), sputtering, plasma enhanced chemical
26 vapour deposition (CVD) and ion-exchange can be used in
27 the fabrication of silica-based planar waveguides doped
28 with rare-earth ions and which display laser
29 characteristics.

30
31 In such laser amplifying waveguides, it is desirable to
32 obtain a high concentration of rare earth ions in order
33 to achieve very compact and efficient devices.

34 However, high concentrations of rare earth ions in a
35 waveguide layer with relatively low solubility can
36 result in the formation of clusters of rare earth ions.

1 The interaction between the rare earth ions in such
2 clusters quenches the excited state required for the
3 lasing process and thus degrades the optical
4 amplification provided by the waveguide.

5
6 Other complications arise in the fabrication of laser
7 waveguides for applications which require single mode
8 transmission, narrow spectral bandwidths, and/or
9 precise control of the lasing wavelength depend
10 critically on their cavity type. Laser waveguides
11 which have butt-coupled mirrors on the waveguide ends
12 or dielectric reflection mirrors are known in the art
13 but suffer to a greater or lesser degree from certain
14 disadvantages; for example, low spectral selectivity.

15
16 Bragg gratings incorporated in a waveguide core can
17 provide enhanced spectral selectivity. The fabrication
18 of such gratings is affected by the host glass
19 composition present in the waveguide core which
20 determine the UV absorption band of the core material
21 and thus its photosensitive properties. For example,
22 if phosphorus is used as a core dopant ion it can
23 alleviate the formation of rare earth ion clusters but
24 has the disadvantage that it reduces the amount of
25 absorption in the UV and thus reduces the
26 photosensitivity of the core. If germanium is used as
27 a core dopant ion it can increase the photosensitivity
28 of the core but has the disadvantage of promoting rare
29 earth cluster formation.

30
31 The introduction of a Bragg grating can be effected in
32 a planar waveguide by a number of known methods which
33 suffer to a greater or lesser degree from certain
34 disadvantages. The invention provides an optical
35 waveguide with multiple core layers which is suitable
36 for forming a laser waveguide with a high degree of

1 spectral selectivity. The waveguide core combines two
2 different types of silica based layers and these core
3 layers obviate or mitigate the aforementioned
4 disadvantages which arise when seeking to fabricate an
5 in-core Bragg grating to enhance the spectral
6 selectivity of the laser waveguide. The waveguide
7 formed enables in-core Bragg grating formation at a
8 range of UV wavelengths above 150 nm.

9

10 SUMMARY OF THE INVENTION

11

12 In accordance with a first aspect of the invention
13 there is provided an optical waveguide with multiple
14 core layers comprising: a substrate; a waveguide core
15 formed on said substrate; and an upper cladding layer
16 embedding said waveguide core; wherein said waveguide
17 core comprises a first core layer and a second core
18 layer.

19

20 Preferably, the substrate comprises silicon and/or
21 silica and/or sapphire.

22

23 Preferably, the substrate includes an intermediate
24 layer. The intermediate layer may include a buffer
25 layer formed on the substrate. The buffer layer may
26 comprise a thermally oxidised layer of the substrate.

27

28 The intermediate layer may further include a lower
29 cladding layer formed on said buffer layer.

30

31 Preferably, the thickness of the buffer layer is in the
32 range 5 μm to 20 μm .

33

34 The second core layer may be formed on the first core
35 layer and said first core layer may be formed on the
36 substrate. Alternatively, the first core layer may be

1 formed on the second core layer and said second core
2 layer may be formed on the substrate. A further first
3 core layer may be formed on the second core layer such
4 that the first core layer sandwiches the second core
5 layer.

6

7 Preferably, the first core layer includes a dopant to
8 permit the first core layer to exhibit a photosensitive
9 response. The first core layer may include silica.

10

11 Preferably, the first core layer includes a germanium
12 oxide and/or a boron oxide. The first core layer
13 dopant may include dopant ions. Preferably, the first
14 core layer dopant ions include tin and/or cerium and/or
15 sodium.

16

17 The second core layer may include a dopant to induce
18 amplification of an optical signal transmitted through
19 said waveguide core. The second core layer may include
20 silica. The second core layer may include a phosphorus
21 oxide. The second core layer dopants may include
22 dopant ions. The second core layer dopant may include
23 a mobile dopant.

24

25 Preferably, the second core layer dopants include a
26 rare earth and/or a heavy metal and/or compounds of
27 these elements. More preferably, the rare earth is
28 Erbium or Neodymium.

29

30 Preferably, the refractive indices of the first core
31 layer and the second core layer are substantially
32 equal.

33

34 Preferably, the refractive index of the waveguide core
35 differs from that of the substrate by at least 0.05%.

36

1 Preferably, the thickness of the first core layer is in
2 the range 0.2 μm to 30 μm .

3

4 Preferably, the thickness of the second core layer is
5 in the range 0.2 μm to 30 μm .

6

7 Preferably, the width of the waveguide core lies in the
8 range 0.4 μm to 60 μm .

9

10 The upper cladding layer and the lower cladding layer
11 may comprise the same material. The refractive index
12 of the substrate and the refractive index of the upper
13 cladding layer may be substantially equal.

14

15 In accordance with a second aspect of the invention
16 there is provided a method of fabricating a waveguide
17 comprising the steps of: providing a substrate; forming
18 a waveguide core on the substrate; and forming an upper
19 cladding layer to embed the waveguide core, wherein
20 the waveguide core is formed from a first core layer
21 and a second core layer.

22

23 The formation of the substrate may include the
24 formation of an intermediate layer formed on said
25 substrate. The formation of the intermediate layer may
26 include the formation of a buffer layer. The buffer
27 layer may be formed by thermally oxidising the
28 substrate.

29

30 The formation of the intermediate layer may further
31 include the formation of a lower cladding layer formed
32 on said buffer layer. The formation of the lower
33 cladding layer may include doping said lower cladding
34 layer with a dopant. The dopant may include dopant
35 ions.

36

1 Preferably, the second core layer is formed on the
2 first core layer and the first core layer is formed on
3 the substrate. Alternatively, the first core layer may
4 be formed on the second core layer and said second core
5 layer may be formed on the substrate.

6

7 A further first core layer may be formed on the second
8 core layer such that the first core layer sandwiches
9 the second core layer.

10

11 The steps of forming any one of the substrate, first
12 core layer, the second core layer, and the upper
13 cladding layer may comprise the steps of:

14 depositing each layer; and
15 at least partially consolidating each layer.

16

17 Preferably, any one of the substrate, the first core
18 layer, the second core layer and the upper cladding
19 layer partially consolidated after deposition is fully
20 consolidated with the full consolidation of any other
21 of the first core layer, the second core layer or the
22 upper cladding layer.

23

24 Preferably, the formation of the first core layer
25 includes the doping of the first core layer with a
26 dopant.

27

28 Preferably, the first core layer dopant permits the
29 first core layer to exhibit a photosensitive response.

30

31 Preferably, the formation of the second core layer
32 includes the doping of the second core layer with a
33 dopant.

34

35 Preferably, the second core layer dopant induces
36 amplification of an optical signal transmitted through

1 said waveguide core.

2

3 The formation of the substrate may include the doping
4 of the substrate with a dopant. The dopant may include
5 dopant ions.

6

7 Preferably, the substrate dopant includes a mobile
8 dopant.

9

10 Preferably, said first core layer dopant ions include
11 tin and/or cerium and/or sodium.

12

13 Preferably, said second core layer dopant ions include
14 a rare earth and/or a heavy metal and/or compounds
15 thereof.

16

17 Preferably, said rare earth is Erbium and/or Neodymium.

18

19 Preferably, the concentration of the first core layer
20 dopant is selectively controlled during the formation
21 of the first core layer and the concentration of the
22 second core layer dopant is selectively controlled
23 during the formation of the second core layer so that
24 the refractive index of the first core layer and the
25 refractive index of the second core layer are
26 substantially equal.

27

28 Preferably, the concentrations of the first core layer
29 dopant and second core layer dopant are controlled to
30 give a refractive index for the waveguide core which
31 differs from that of the substrate layer by at least
32 0.05%.

33

34 The lower cladding layer and said buffer layer may be
35 formed substantially in the same step. At least one of
36 the substrate, the first core layer, the second core

1 layer, and the upper cladding layer may be deposited by
2 a Flame Hydrolysis Deposition process and/or Chemical
3 Vapour Deposition process. The Chemical Vapour
4 Deposition process may be a Low Pressure Chemical
5 Vapour Deposition process or a Plasma Enhanced Chemical
6 Vapour Deposition process.

7
8 Preferably, the consolidation is by fusing using a
9 Flame Hydrolysis Deposition burner. Alternatively, the
10 consolidation may be by fusing in a furnace.

11
12 The step of fusing the lower cladding layer and the
13 step of fusing the first core layer and/or the second
14 core layer may be performed simultaneously. The
15 waveguide core may be formed from the first core layer
16 and the second core layer using a dry etching technique
17 and/or a photolithographic technique and/or a
18 mechanical sawing process. The dry etching technique
19 may comprise a reactive ion etching process and/or a
20 plasma etching process and/or an ion milling process.

21
22 The waveguide core formed from the first core layer and
23 the second core layer may be square or rectangular in
24 cross-section.

25
26 In accordance with a third aspect of the invention
27 there is provided a laser waveguide with multiple core
28 layers comprising a waveguide according to the first
29 aspect of the invention, the laser waveguide further
30 comprising:

31 at least one grating formed in said waveguide
32 core.

33
34 Preferably, the laser waveguide further comprises at
35 least one optical interference mirror.

36

1 More preferably, the optical interference mirror is
2 provided at the input of the waveguide. The
3 interference mirror may be butt-coupled to or directly
4 deposited at the input of the waveguide.

5
6 The laser waveguide may include two mirrors and a
7 grating. Alternatively, the laser waveguide may
8 include one mirror and two gratings. Alternatively,
9 the laser waveguide may include three gratings. The
10 grating formed may be a Bragg grating. The grating may
11 form an output coupler for said laser waveguide.

12
13 The laser waveguide may further comprise an optical
14 interference mirror butt coupled to or directly
15 deposited at the output of the waveguide.

16
17 In accordance with a fourth aspect of the invention
18 there is provided method of fabricating a laser
19 waveguide, comprising forming a waveguide according to
20 the method of the second aspect of the invention, the
21 method of fabricating the laser waveguide further
22 including the steps of:

23 forming at least one grating in said waveguide
24 core.

25
26 The method may further include the step of attaching at
27 least one optical interference mirror to the waveguide.

28
29 The optical interference mirror may be attached to an
30 input of the waveguide.

31
32 The grating may be formed using a laser operating at a
33 wavelength in the range of 150 nm to 400 nm through a
34 phase mask deposited on top of said upper cladding
35 layer of the waveguide. The mask may be a quartz mask.
36 The grating may be formed using a using an interference

1 side writing technique. The grating may be formed
2 using a direct writing technique. The grating formed
3 may be a Bragg grating.
4

5 Preferably, in the above method, the optical
6 interference mirror is butt-coupled to or directly
7 deposited at the input of the waveguide.
8

9 The method may further comprise the step of attaching a
10 second optical interference mirror to the output of the
11 waveguide.
12

13 DESCRIPTION OF THE DRAWINGS

14

15 Embodiments of the present invention will now be
16 described, by way of example only, with reference to
17 the accompanying drawings, in which:-
18

19 Figs. 1A to 1C are schematic cross-sectional diagrams
20 of a waveguide with multiple core layers during various
21 stages of fabrication.
22

23 Fig. 2A is a schematic representation of a laser
24 waveguide formed from the waveguide shown in Figs. 1A
25 to 1C; and
26

27 Fig. 2B is a detail, to an enlarged scale, of the
28 structure shown in Fig. 2A.
29

30 DETAILED DESCRIPTION OF THE INVENTION

31

32 Referring now to the drawings, Figs. 1A to 1C
33 illustrate schematically stages in the fabrication of a
34 waveguide with a multi-layered core according to the
35 invention.
36

1 Referring now to Fig. 1A, there is illustrated a
2 waveguide 1 which is fabricated from a substrate 2.
3 The substrate 2 comprises a silicon wafer. However,
4 other suitable substrates including silica and
5 sapphire, may be used.

6
7 A silica buffer layer 3, comprising a thermally
8 oxidised layer of the substrate 2, is formed on the
9 substrate 2. The thickness of the buffer layer 3 is 15
10 μm which lies in a preferred range of 5 μm to 20 μm .

11
12 A suitable method, for example, a flame hydrolysis
13 deposition (FHD) method, is used to deposit a first
14 core layer 4 on top of the buffer layer 3. The
15 thickness of the first core layer 4 is 2 μm which lies
16 in a preferred range of 0.2 μm to 30 μm .

17
18 The material included in the first core layer 4
19 provides a high photosensitive response to an optical
20 signal. In a preferred embodiment, the first core
21 layer 4 includes a high concentration of Germanium
22 dopant, for example 17 %wt, co-doped with Boron, for
23 example 5 %wt. Other dopant ions can be included, or a
24 mixture of dopant ions, for example, tin, cerium,
25 and/or sodium.

26
27 The dopant and co-dopants are introduced during the
28 deposition of the first core layer 4. The Germanium
29 dopant induces a high photosensitive response and the
30 Boron co-dopant lowers the refractive index induced by
31 the high level of Germanium in the first core layer 4.
32 The concentrations of the dopant and co-dopant are
33 adjusted to 17% wt and 5% wt to give a difference
34 between the refractive index of the first core layer 4
35 and the refractive index of the buffer layer 3 of 0.75%
36 which lies in a preferred range of 0.05% to 2.0% .

1 The first core layer 4 is then consolidated by a
2 suitable method, for example by a second pass of the
3 FHD burner or by consolidating the waveguide 1 in an
4 electrical furnace.

5

6 Fig. 1B shows a further stage in the fabrication of the
7 waveguide 1 in which a second core layer 5 is formed on
8 the first core layer 4.

9

10 The second core layer 5 is deposited on the first core
11 layer 4 using a suitable method, for example FHD, and
12 is then suitably consolidated, for example, in an
13 electrical furnace.

14

15 The second core layer 5 is doped with rare earth dopant
16 ions, for example Er^{+3} , using an aerosol doping
17 technique, and co-doped, for example, with Phosphorus
18 during the deposition of the second core layer 5. The
19 thickness of the second core layer 5 is $4\mu\text{m}$, which lies
20 in the range of $0.2\mu\text{m}$ to $30\mu\text{m}$.

21

22 Alternative methods can be used to dope the second core
23 layer 5 such as solution doping. Preferably, the dopant
24 and co-dopant are simultaneously introduced in a
25 controlled manner during the deposition of the second
26 core layer 5. The concentrations of the dopant and co-
27 dopant can be controlled so that the second core layer
28 5 provides the desired signal gain for optical signals
29 propagating through the waveguide and also to ensure
30 that the refractive index of the second core layer 5 is
31 matched to the refractive index of the first core layer
32 4. In this embodiment, the indices are substantially
33 matched. Alternatively, the first core layer 4 and the
34 second core layer 5 can be subjected to a further
35 process, for example, UV trimming, to effect matching
36 of their refractive indices.

1 The photosensitive response of the first core layer 4
2 in combination with the optical signal gain of the
3 second core layer 5 effect the overall level of optical
4 signal amplification provided by the waveguide 1.

5
6 A waveguide core 6 is then formed from the first core
7 layer 4 and the second core layer 5 by using a suitable
8 method, for example conventional photolithographic
9 and/or reactive ion etching (RIE) methods. A portion
10 of the second core layer 5 is suitably masked and the
11 unwanted portions of the second core layer 5 and the
12 underlying first core layer 4 are etched away to leave
13 the waveguide core 6. The overall dimensions of the
14 waveguide core 6 formed are $6\mu\text{m} \times 6\mu\text{m}$ which is in a
15 preferred range of $0.4\mu\text{m} \times 0.4\mu\text{m}$ to $60\mu\text{m} \times 60\mu\text{m}$.

16
17 The co-dopant, here Boron, in the first core layer 4
18 reduce the refractive index of the waveguide core 6 and
19 enable single mode operation even for large waveguide
20 cores, for example waveguide cores whose dimensions are
21 in the range of $0.4\mu\text{m} \times 0.4\mu\text{m}$ to $60\mu\text{m} \times 60\mu\text{m}$. The co-
22 dopant in the first core layer 4 can also provide other
23 advantages such as enabling higher refractive index
24 changes to occur during later stages of fabrication of
25 a waveguide with multiple core layers.

26
27 The first core layer 4 effectively can reduce the
28 optical signal gain provided by the second core layer
29 5. It is thus advantageous for the first core layer 4
30 to be as photosensitive as possible in particular as
31 the refractive index modulation no longer occurs over
32 the entire volume of the waveguide core 6.

33
34 Fig. 1C shows a further stage in the fabrication of the
35 waveguide. An upper cladding layer 7 is deposited on
36 the waveguide core 6 using an FHD method. The upper

1 cladding layer 7 embeds the waveguide core 6. The
2 upper cladding layer 7 is doped during deposition, for
3 example with Phosphorus and Boron, to adjust its
4 refractive index until the refractive index of the
5 upper cladding layer 7 matches the refractive index of
6 the buffer layer 3. The upper cladding layer 7 is then
7 consolidated, for example in an electrical furnace.

8
9 In a second preferred embodiment of the invention, a
10 lower cladding layer is formed on top of the buffer
11 layer 3 before the first core layer 4 is deposited and
12 in which the level of dopant in the upper cladding
13 layer 7 is adjusted until the refractive index of the
14 upper cladding layer 7 matches that of the lower
15 cladding layer. The lower cladding layer can be
16 deposited and consolidated using the same techniques as
17 the upper cladding layer 7.

18
19 In an alternative layer structure the first core layer
20 4 may be deposited on top of the second core layer 5 or
21 respective first core layers 4 may be provided both
22 below and on top of the second core layer 5. The core
23 layer 5 is then sandwiched between two photo-sensitive
24 first core layers 4 increasing the coupling coefficient
25 of the device.

26
27 It is possible also, for certain applications, to dope
28 the photo-sensitive first core layer 4 with a small
29 amount of rare earth ions.

30
31 Referring now to Figs. 2A and 2B of the drawings, there
32 is shown a schematic diagram of laser waveguide
33 according to the invention. Figs. 2A and 2B show a
34 cross-section parallel to the longitudinal axis of the
35 laser waveguide core, such that the waveguide core is
36 seen only in profile.

1 Fig. 2A shows a planar laser waveguide 10 incorporating
2 a Bragg grating 11. The laser waveguide 10 includes a
3 silicon substrate layer 12 and a silica buffer layer 13
4 comprising a thermally oxidised layer of the substrate
5 12. The buffer layer 13 is formed on the substrate
6 layer 12.

7
8 Fig. 2B is an enlarged view of a section of Fig. 2A. A
9 first core layer 14 is deposited and consolidated on
10 the buffer layer 13 and second core layer 15 is
11 deposited and consolidated on the first core layer 14
12 using the techniques described above for the deposition
13 and consolidation of first and second core layers 4 and
14 5 in the waveguide 1. The first core layer 14 can
15 alternatively be formed on an lower cladding layer (not
16 shown) formed on buffer layer 13.

17
18 The second core layer 15 is doped with neodymium
19 instead of the erbium used as a dopant in the second
20 core layer 5. Fig. 2A represents a cross-section
21 through the laser waveguide 10 parallel to the
22 direction of light propagation through the waveguide 10
23 (i.e., normal to the cross-sectional plane through the
24 waveguide shown in Fig. 1C). The waveguide core 16 is
25 formed from said first core layer 14 and said second
26 core layer 15 using the same technique described above
27 for the formation of the first core layer 4 and the
28 second core layer 15.

29
30 An upper cladding layer 17 is then deposited on the
31 second core layer 15 and the grating 11. The upper
32 cladding layer 17 is deposited and consolidated using
33 the same methods as described above for the deposition
34 and consolidation of the upper cladding layer 7 in the
35 fabrication of waveguide 1.

36

1 The laser cavity of the laser waveguide 10 is
2 fabricated by writing the Bragg grating 11 into a
3 generally central portion of the first core layer 14
4 and the second core layer 15. Conventionally, the
5 Bragg grating 11 may be written using a KrF excimer
6 laser operating at 248 nm through a quartz phase mask
7 deposited on top of the upper cladding layer.

8

9

10 An input 18 of the laser waveguide 10 provides an
11 optical signal at a pump wavelength to the laser
12 waveguide 10. An optical interference mirror 19 butt-
13 coupled to the input end 18 of the laser waveguide 10
14 has a high reflectivity ($R_{sig} = 99.9\%$) around the maxima
15 of the desired output wavelength and has a high
16 transmittance at the pump wavelength ($T_{pump} > 95\%$). The
17 grating 11 forms an output coupler at the output 20 of
18 the laser waveguide 10.

19

20 The grating 11 is designed for use at 1050 nm and the
21 reflectivity of the grating 11 formed saturates at 80%.
22 The phase mask used to form the grating 11 has a pitch
23 of 720 nm. In other embodiments, however, it is
24 possible to form gratings 11 which can be used at a
25 wavelength in the range of 500 nm to 2100 nm by using
26 suitable phase masks.

27

28 In another embodiment of a laser waveguide, a grating
29 11 can be provided at both the input 18 and the output
30 20 of the laser waveguide 10, preferably with both
31 gratings having substantially the same Bragg wavelength
32 thus providing a distributed Bragg reflection laser
33 (DBR).

34

35 In yet another embodiment, a distributed feedback laser
36 (DFB) can also be formed by having a grating extending

1 along the length of the gain cavity formed by the core
2 layer 5.

3
4 Further, a multicavity laser can be formed by butt-
5 coupling another mirror to the output end of the laser
6 waveguide 10. These external mirrors can be bulk
7 mirror butt-coupled or mirrors directly deposited on
8 the ends of the waveguide. A multiple wavelength laser
9 can be provided by photoimprinting a sampled grating in
10 the waveguide core, with precise control of channel
11 spacing. Additionally, a multiple wavelength laser can
12 be achieved by exposing the same core area to very
13 similar UV patterns, with each exposure determining
14 each one of the emission wavelengths of the
15 superimposed Bragg gratings. An additional grating can
16 be defined to provide gain equalisation for the several
17 wavelengths.

18
19 Thus, a multicavity laser can be constructed by using
20 two mirrors and a grating, one mirror and two gratings,
21 or indeed three gratings.

22
23 Still further, in a different application, for example,
24 optical amplifiers, a grating can also be formed on the
25 first core layer 4 to act as a "tap" to flatten optical
26 gain spectra.

27
28 While several embodiments of the present invention have
29 been described and illustrated, it will be apparent to
30 those skilled in the art once given this disclosure
31 that various modifications, changes, improvements and
32 variations may be made without departing from the
33 spirit or scope of this invention.